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Investigation of the mixing layer of underexpanded supersonic jets by particle image velocimetry

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ABSTRACT

The present experimental study focuses on some properties of the turbulence and the shock-cell structure in underexpanded supersonic jets, which are of practical relevance in air transport. Choked jets at fully expanded Mach numbers $M_j = 1.10$, 1.15, 1.35 and 1.50 are investigated using particle image velocimetry. The strength of the shock-cell structure is studied from mean velocity profiles, both in the jet core and in the mixing layer. The general geometry of the latter and its location relatively to the mean shock-cell structure are established. Furthermore, detailed accounts of mixing layer thickness, turbulence levels, spatial correlations and intrinsic turbulence length scales are given. While the mean velocity variations related to the shock-cell structure extend up to the subsonic part of the studied jets, their mixing layer is found to be mostly located in the subsonic region. Some of the observed turbulence properties, like the mixing layer thickness and turbulence levels, are close to what is found for subsonic jets. The effect of the shock-cell structure on turbulence is however visible for $M_j \geqslant 1.35$. The spatial correlations of turbulence are used to estimate intrinsic turbulence length scales and these are found to be of the order of the shock-cell length. These data are used to make some comments upon the generation mechanism of shock-associated noise, a noise component produced by imperfectly expanded supersonic jets.

1. Introduction

A large part of the current commercial aircraft is powered by a high-bypass-ratio engine, in which a hot primary stream is embedded in a cold secondary (fan) flow. At the typical subsonic cruise conditions, the secondary jet becomes underexpanded, meaning that the pressure in the nozzle exit plane is greater than the ambient pressure. This situation induces a shock-cell structure inside the flow, which brings the jet pressure down to the ambient pressure through a pattern of expansions and compressions. Another particularity of such flows compared to subsonic jets is the emission of a specific noise component called the shock-associated noise. This is made up of a tonal part, also known as screech, and a broadband part.

The shock-cell structure of underexpanded jets was much studied experimentally, especially through extensive static pressure measurements (Norum and Seiner, 1982; Norum and Shearin, 1988), and also by the authors of the present paper (André et al., 2014). However, detailed accounts of the turbulence in such jets are scarce. Seiner and Norum (1980) measured turbulence levels and spectra using a hot film probe. Panda and Seasholtz (1999) obtained the coherent part of the density fluctuations in choked jets using the Rayleigh scattering technique and related this to the screeching process. Several studies applied particle image velocimetry (PIV) to these flows. Jerónimo et al. (2002) investigated the first shock cell of an overexpanded jet showing a Mach disc. Alkislar et al. (2003) separated the random from the coherent turbulent motion in the mixing layer of a screeching rectangular jet using stereoscopic PIV, and pinpointed the relation between coherent vortices and screech generation. Bridges and Wernet (2008) applied high-speed PIV to screeching and non-screeching supersonic jets, mainly focusing on turbulence spectra.

The objective of the present experimental study is to focus on some properties of the turbulence and the shock-cell structure in the mixing layer of underexpanded supersonic jets using particle image velocimetry. To begin with, the strength of the shock-cell structure in the mixing layer is estimated. Then, a study of the turbulence of these jets is reported. It addresses the overall structure of the mixing layer, its thickness, turbulence levels, spatial correlations and turbulence length scales in the convected frame. In the

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concluding remarks, some comments upon the generation mechanism of shock-associated noise are made in light of the obtained data.

2. Experimental methods

The facility employed in the present work has already been used to study single-stream supersonic jets (André et al., 2014) as well as co-axial jets (André et al., 2011). The configuration considered here is the latter one, with the outer stream set at a Mach number of 0.05 to seed the surroundings of the inner, supersonic jet, during the PIV measurements.

The supersonic jet flow originates from a continuously operating compressor mounted upstream of an air drier. It exhausts through a round, contoured and convergent nozzle of diameter $D = 38.7$ mm. Since the underexpanded jets exiting typical turbofan engines of civil aircraft do not seem to emit the tonal component of shock-associated noise (screech noise), and considering that this component has a strong impact on the jet dynamics (André et al., 2012; André et al., 2013), it appears relevant to eliminate it in the small-scale study. For that purpose, a screech-suppressing nozzle is employed, showing shallow notches carved into its lip. As indicated in André et al. (2013), this nozzle non-intrusively suppresses screech. The reservoir temperature T_t is measured upstream of the exit. Here, the jets are unheated and $T_t \approx 30\,^{\circ}\mathrm{C}$. The nozzle pressure ratio (NPR), defined as the ratio between jet stagnation pressure and ambient pressure, is set by measuring the wall static pressure fifteen nozzle diameters upstream of the exit. In the following, results for jets of ideally expanded Mach numbers $M_j = 1.10$, 1.15, 1.35 and 1.50 are presented, corresponding to NPR = 2.14, 2.27, 2.97 and 3.67, respectively. The convective Mach numbers M_c of these jets are 0.49, 0.51, 0.59 and 0.63 for increasing M_j.

A conventional Z-type schlieren system is used to visualise the flow. It consists of a light-emitting diode, two 203.2 mm-diameter f/8 parabolic mirrors, a straight knife-edge set perpendicular to the flow direction and a high-speed Phantom V12 CMOS camera.

Particle image velocimetry has also been applied to measure velocity in a plane containing the jet axis and a notch. Illumination is provided by a pulsed double-cavity Nd:YLF Quantronix Darwin Duo laser and the sheet thickness is 1.7 mm (±0.3 mm). The supersonic jet is seeded with olive oil by means of custom-designed Laskin nozzle generators. The mean particle size is known to be around 1 μm. The secondary flow is seeded by smoke. Both seeding devices are mounted far enough upstream of the exit so that the particle concentration in each flow is approximately uniform. Two CMOS cameras of sensor size 1280×800 pixels^2 are set side by side to double axially the field of view available, which covers a length of about two jet diameters. In the radial direction, only one half of the jet is visualised, since the other part can be deduced by axisymmetry. The PIV set-up is mounted on a frame which can be translated in the jet direction; an axial extent of $12D$ is studied here, meaning that the entire field has been acquired in six parts. For each new location of the frame, a calibration of the camera images is performed using a three-dimensional LaVision plate, the jet operating conditions are reset and 2000 image pairs are recorded. The acquisition frequency of the image pairs is 500 Hz and the magnifying factor for each camera is about 0.05 mm.pixel^{-1}. The delay between the images of each pair is set to 3 μs for all jet conditions. Vector field calculation is performed by a multigrid FFT-based technique using the LaVison DaVis 7.2 software. In all but the last iteration of the velocity computation procedure, the calculation is a two-step process; a 25%-overlap of the interrogation windows is set and no window ponderation is used. For the last iteration, three computational steps are set, as well as a 50%-overlap and an isotropic Gaussian window ponderation. The final correlation windows are of size 8×8 pixels^2, leading to a vector density of one every 0.2 mm, or approximately 190 vectors across the supersonic jet diameter.

The behaviour of the seeding particles in imperfectly expanded jets was studied by André et al. (2014) from laser Doppler velocimetry (LDV) data. It was concluded that the particles followed accurately the flow in slightly underexpanded jets and even in the presence of a Mach disc. The mean velocity results obtained by PIV were compared to LDV profiles and a good agreement was found; the latter technique was validated in André et al. (2014). Our results were also found to be in good agreement with RANS simulations performed during a companion study (Henry et al., 2012).

In the following, the origin of the coordinates is taken on the jet axis, in the nozzle exit plane. The variable x will denote the axial direction and y the transverse direction.

3. Results

In order to introduce the shock-cell structure typical of underexpanded supersonic jets, spark schlieren images of two jets at $M_j = 1.10$ and 1.50 are presented in Fig. 1. Owing to the orientation of the knife-edge in the schlieren set-up, axial gradients of density are visualised here. The well-known quasi-periodic shock-cell pattern is visible. The light (dark) regions correspond to expansion (compression) regions, see Panda and Seasholtz (1999) and André et al. (2014) for more details about the mean shock-cell pattern. At $M_j = 1.50$, a small normal shock, called Mach disc, forms in the first shock cell. Turbulent fluctuations are also visible in these pictures. The fact that they even appear in the jet core region is a result of the integration of the density gradients across the entire jet. Other schlieren images of such jets, also with different knife-edge orientations, can be found in Powell (1953), Seiner and Norum (1979) or Panda (1999), among others.

3.1. Shock-cell structure in the mixing layer

Usually, pressure measurements are used for quantifying the strength of the mean flow gradients (Norum and Seiner, 1982; Norum and Shearin, 1988) but they are generally confined to the jet core. We focus here on the mean flow gradients near the mixing layer. To that end, the velocity gradients in the mixing layer are deduced from the mean velocity maps obtained by PIV, and compared to those existing in the jet core. The extreme values of M_j, namely 1.10 and 1.50, are considered.

A map of mean velocity for $M_j = 1.10$ is presented in Fig. 2, along with calculated mean flow streamlines. The mean velocity on these streamlines, which are almost straight at this low underexpansion, is shown in Fig. 3(a), while the computed gradients of the mean velocity along the streamlines are displayed in (b). It is visible that the gradients wear off when moving downstream or toward the mixing layer and that they remain small in the entire flow. It is also worth noting that the gradients are still present in the subsonic region of the jet.

The flow with $M_j = 1.50$ is now studied. The cartography of the mean velocity is displayed in Fig. 4. The streamlines present a curvature, which comes from the lateral expansions and constrictions of the jet plume, induced by the stronger underexpansion. Because of strong gradients both in the axial and radial directions in the Mach disc region, the velocity estimates from the particle image analysis are there only approximate. The velocity on the jet centreline is nonetheless shown in order to compare the estimated strong gradients associated with the Mach disc with those observed elsewhere in the jet. A signature of the Mach disc is the